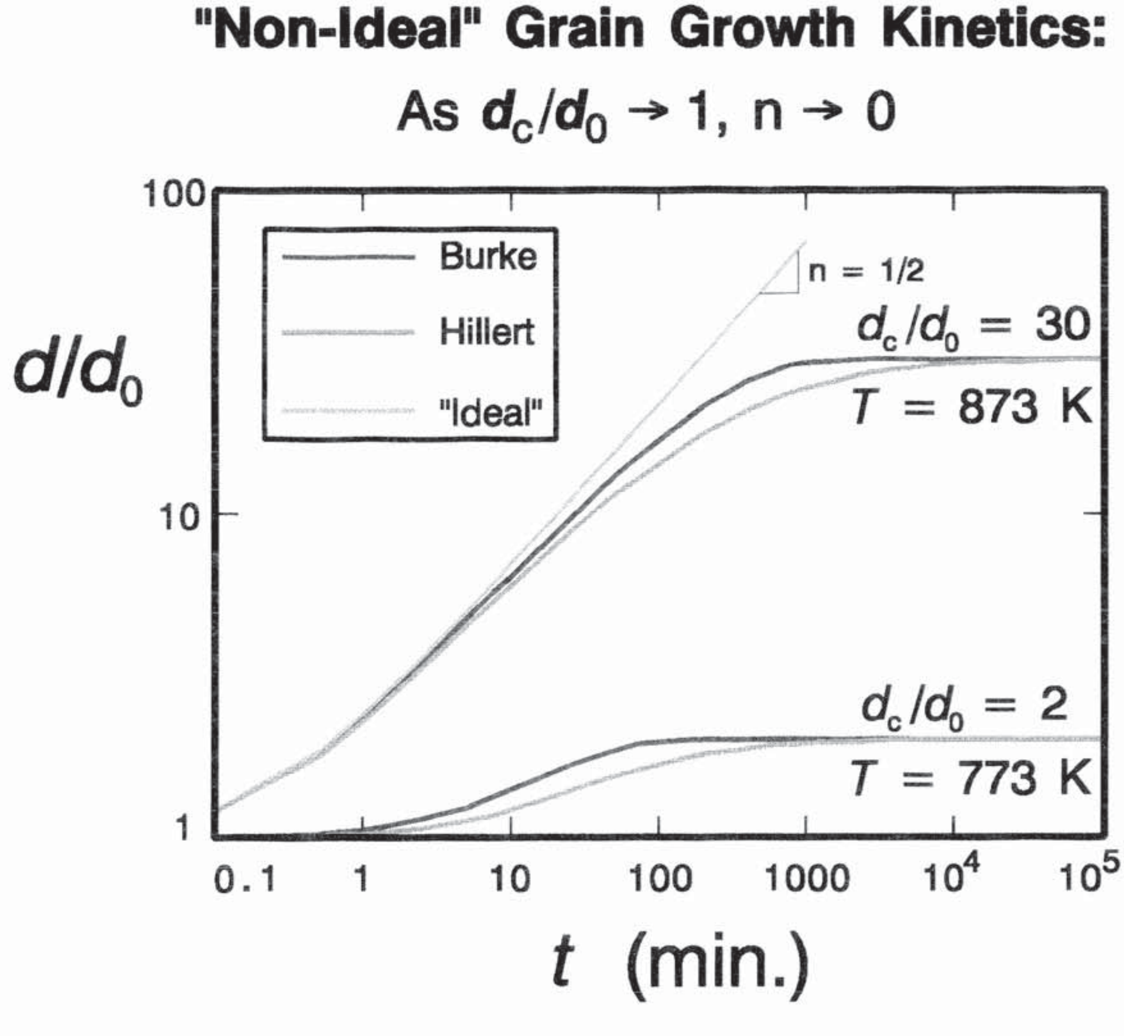
APPENDIX
7475 ALUMINUM
GRAIN GROWTH DATA



CAPTION: "Non-Ideal" Grain Growth Kinetics

Burke's (1949) grain growth rate for particle containing materials such as 7475 Al is

$$\dot{\boldsymbol{d}} = M_B[2\Gamma(1/\boldsymbol{d} - 1/\boldsymbol{d}_c)] = M_B(2\Gamma/\boldsymbol{d})[1 - \boldsymbol{d}/\boldsymbol{d}_c].$$

Here, the grain boundary mobility M_B is, for example, $M_B = m_B(\Omega/\delta)$, ($m_B \equiv D_B/kT$, Ω = *atomic volume*, δ = *grain boundary width*, and D_B = *grain boundary diffusivity*); Γ is the grain boundary surface tension, $\boldsymbol{d}$ the average grain size, and $\boldsymbol{d}_c$ the limiting grain size. Upon integration this grain growth rate yields the following grain growth kinetics:

Burke $$\frac{\boldsymbol{d}_0 - \boldsymbol{d}}{\boldsymbol{d}_c} + \ln\left(\frac{\boldsymbol{d}_c - \boldsymbol{d}_0}{\boldsymbol{d}_c - \boldsymbol{d}}\right) = \frac{2\Gamma}{\boldsymbol{d}_c^2} M_B t,$$

where $\boldsymbol{d}_0$ is the initial grain size. If $1/\boldsymbol{d}_c \equiv 0$, then Burke's grain growth rate integrates to give the *grain growth "law"* (Atkinson 1988) or, *"ideal" grain growth kinetics*:

"Ideal" $$\boldsymbol{d}^2 - \boldsymbol{d}_0^2 = 4\Gamma M_B t.$$

Hillert's (1965) grain growth rate is $$\dot{\boldsymbol{d}} \approx \tfrac{1}{3} X_d M_B(2\Gamma/\boldsymbol{d})[1 - \boldsymbol{d}/\boldsymbol{d}_c]^2,$$

where X_d is the defect fraction of the cellular array, a measure of the grain size distribution. This grain growth rate integrates to (Sherwood and Hamilton 1993)

Hillert $$\frac{\boldsymbol{d}_c(\boldsymbol{d} - \boldsymbol{d}_0)}{(\boldsymbol{d}_c - \boldsymbol{d})(\boldsymbol{d}_c - \boldsymbol{d}_0)} + \ln\left(\frac{\boldsymbol{d}_c - \boldsymbol{d}}{\boldsymbol{d}_c - \boldsymbol{d}_0}\right) = \tfrac{2}{3} X_d[\Gamma M_B/\boldsymbol{d}_c^2]t.$$

Burke's and Hillert's grain growth kinetics are *"non-ideal"*: the *grain growth exponent*, n, is n < 1/2, where $n \equiv \log[\boldsymbol{d}(t_2)/\boldsymbol{d}(t_1)]/\log(t_2/t_1)$. If $\boldsymbol{d}_c >> \boldsymbol{d}_0$ then n = 1/2. As reported by Burke (1949) for a high purity brass: $\boldsymbol{d}_0 = 0.005$ mm; $\boldsymbol{d}_c(773\ \text{K}) \equiv 0.01$ mm, and $\boldsymbol{d}_c(873\ \text{K}) \equiv 0.15$ mm; $2\Gamma M_B \equiv 5.31\times10^5\exp(-20{,}000/T)$ mm²/min for "Ideal" and Burke; $\tfrac{2}{3}\Gamma X_d M_B \equiv 5.31\times10^5\exp(-20{,}000/T)$ mm²/min for Hillert.

The 7475 Al alloy discussed in Chapter Two, Section 5, was fully recrystallized and annealed with the composition shown in Table I; it was sheet formed to a thickness of 1.52 mm. This material exhibits "non-ideal" grain growth during annealing (Sherwood and Hamilton 1993). See Atkinson's (1988) review article and Burke (1949), Hillert (1965), Chopra and Niessen (1973), Morral and Ashby (1974), Chen (1987), Gore *et al.* (1989), Sherwood and Hamilton (1993), and Rios (1994), for further discussions of "non-ideal" grain growth. Grain dimensions for the 7475 Al alloy resulting from annealing and superplastic deformation are reported and discussed here.

Table I. **Alloy Content of 7475 Al Sheet Material (weight percent)**

Zn	Mg	Cu	Cr	Fe	Si	Ti	Mn	Al
5.66	2.13	1.48	0.20	0.08	0.04	0.02	0.01	90.4

Grain dimensions, d_L, d_{LT} and d_{ST}, were determined from counting at least one-hundred intercepts for each of the three principal orthogonal directions with respect to the rolling direction, longitudinal (rolling direction), long-transverse and short-transverse, respectively. The average grain size, $\boldsymbol{d}$, reported here is just the arithmetic average of these dimensions.

TABLE II. **7475 Al Grain Dimensions (μm) from Annealing at 450, 475, 516, 525 and 540 °C**

(Initial, t = 0, dimensions: d_{ST} = 5.4, d_{LT} = 9.4, and d_L = 12.9 μm, for $\boldsymbol{d}_0$ = 9.2 μm.)

T (°C):	450				475				516			
t (min.)	d_{ST}	d_{LT}	d_L	$\boldsymbol{d}$	d_{ST}	d_{LT}	d_L	$\boldsymbol{d}$	d_{ST}	d_{LT}	d_L	$\boldsymbol{d}$
5	6.1	8.6	13.5	9.4	7.5	9.9	11.9	9.8	6.9	9.7	12.9	9.8
15	6.3	9.5	13.2	9.7	6.6	10.0	12.5	9.7	-----	-----	-----	-----
30	6.4	9.9	13.8	10.0	8.0	11.1	13.2	10.8	6.6	12.1	14.1	10.9
60	-----	-----	-----	-----	8.0	11.7	16.8	12.2	8.0	11.4	14.2	11.2
240	6.8	10.3	14.2	10.4	7.3	12.0	16.4	11.9	9.3	12.0	15.1	12.1
480	6.3	9.8	14.3	10.1	7.7	12.2	16.4	12.1	9.2	13.9	15.7	12.9
1440	6.9	9.6	15.4	10.6	8.0	13.1	17.7	12.9	9.7	14.7	17.1	13.8
4320	-----	-----	-----	-----	-----	-----	-----	-----	11.4	16.7	18.9	15.7
10080	7.2	12.1	14.8	11.4	9.6	14.6	19.3	14.5	13.5	16.4	22.9	17.6

T (°C):	525				540			
t (min.)	d_{ST}	d_{LT}	d_L	$\boldsymbol{d}$	d_{ST}	d_{LT}	d_L	$\boldsymbol{d}$
5	6.8	10.4	12.9	10.0	8.1	10.4	14.4	11.0
15	6.8	11.6	12.9	10.4	9.1	11.4	14.8	11.8
30	8.0	10.8	14.0	10.9	9.3	12.1	16.9	12.8
60	7.6	11.9	14.6	11.4	10.5	13.5	19.0	14.3
240	8.3	13.3	15.5	12.4	11.9	14.2	20.2	15.4
480	8.3	14.1	16.1	12.8	12.6	14.8	21.3	16.2
1440	12.5	15.5	18.9	15.6	12.8	17.5	27.1	19.1
10080	13.7	16.2	23.7	17.9	14.3	18.6	30.3	21.1

Grain dimensions for the annealed material are given in Table II; only small increases in grain size occur even after prolonged exposure to very high temperatures. Average grain sizes from this data set are represented by

$$\boldsymbol{d}(t,T) = [\boldsymbol{d}_0^{1/n} + Kt]^n, \tag{1}$$

with the parameters K and n, presented in Table III (Sherwood and Hamilton 1993); see Figure 53. Approximate values for these parameters are suggested by linear regression of the experimental data, which yield the values n′ and K' at each temperature through the relation $\boldsymbol{d} = K't^{n'}$. Values of K and n listed in Table III were determined by trial and error, using these regression values and the initial grain size. Note that n $<<$ 1/2 and n decreases with decreasing annealing temperature; the 7475 Al alloy exhibits "non-ideal" grain growth.

TABLE III. **Grain Growth Parameters for 7475 Al** (for $\boldsymbol{d}$ in μm and t in s)

$$\boldsymbol{d}(t,T) = [\boldsymbol{d}_0^{1/n} + Kt]^n \approx K't^{n'}$$

Temperature ($^\circ$C)	K'	n′	log(K)	1/n
450	8.28	0.0226	31.7	35.7
475	7.29	0.0513	13.0	16.2
516	6.20	0.0740	7.85	11.1
525	5.90	0.0827	8.13	11.0
540	6.60	0.0893	8.94	11.0

Tensile tests were conducted in air at temperatures of 450, 475, 516 and 525 °C, for strain rates in the range 10^{-4} to 10^{-2} s^{-1} using a screw-driven machine modified with a computer program that allowed the cross-head speed to continually increase with specimen elongation. In this way the average strain rate imposed on the specimen was kept constant. After tensile testing specimens were reheated to the test temperature for 5 minutes and water quenched to aid metallographic examinations. A specimen exposed to the thermal cycle of the test apparatus was used to determine the grain size at the start of deformation, $\boldsymbol{d}_0$, for each deformation temperature: $\boldsymbol{d}_0 = 9.3$, 10.7, 10.6, and 10.7 μm, for the temperatures 450, 475, 516, and 525 °C, respectively. Practically no grain growth is obtained when the 7475 Al alloy is annealed for time periods associated with tensile testing: the as-received grain size, $\boldsymbol{d}(t = 0) \equiv \boldsymbol{d}_0 = 9.2$ μm, is increased by less than two microns.

Grain dimensions for the deformed material are given in Tables IV an V.

Table IV. **7475 Al Grain Dimensions (μm) from Deformation at 450, 475 and 516 $^{\circ}$C**

(Initial dimensions. 450 $^{\circ}$C: d_{ST} = 5.7, d_{LT} = 9.8, and d_L = 12.5 μm, for $\boldsymbol{d}$ = 9.3 μm;

475 $^{\circ}$C: d_{ST} = 6.7, d_{LT} = 11.2, and d_L = 14.2 μm, for $\boldsymbol{d}$ = 10.7 μm;

516 $^{\circ}$C: d_{ST} = 6.6, d_{LT} = 11.3, and d_L = 13.9 μm, for $\boldsymbol{d}$ = 10.6 μm)

$\dot{\varepsilon}$/s	10^{-2}			5×10^{-3}			10^{-3}			5×10^{-4}			10^{-4}		
ε	0.3	0.6	1.0	0.3	0.6	1.0	0.3	0.6	1.0	0.3	0.6	1.0	0.3	0.6	1.0
450 $^{\circ}$C															
d_{ST}	5.7	5.3	4.3	5.3	5.5	5.4	6.2	6.3	5.9	6.9	6.2	6.1	6.3	6.4	7.9
d_{LT}	9.8	12.4	10.6	11.3	11.2	9.9	13.6	14.0	16.0	14.7	11.9	12.8	14.1	14.9	16.1
d_L	11.4	14.6	18.8	13.9	18.3	21.0	14.4	17.3	18.9	15.4	18.0	19.1	16.1	17.4	21.7
$\boldsymbol{d}$	9.0	10.8	11.2	10.2	11.7	12.1	11.4	12.5	13.6	12.3	12.0	12.7	12.2	12.9	15.2
475 $^{\circ}$C															
d_{ST}	5.5	5.9	6.0	5.4	6.4	6.6	6.7	6.7	7.3	7.6	8.0	7.9	7.7	7.8	8.6
d_{LT}	13.4	11.6	11.5	12.1	12.8	11.7	15.7	13.3	15.7	17.1	16.7	16.7	19.1	18.1	17.6
d_L	13.2	14.7	17.6	14.6	16.3	17.6	17.6	19.2	20.8	17.6	18.6	20.3	18.6	21.9	24.3
$\boldsymbol{d}$	10.7	10.7	11.7	10.7	11.8	12.0	13.3	13.1	14.6	14.1	14.4	15.0	15.1	15.9	16.9
516 $^{\circ}$C															
d_{ST}	7.3	8.1	----	7.8	7.7	7.6	7.8	7.7	8.8	8.4	8.9	8.7	8.6	8.6	10.2
d_{LT}	17.3	17.5	----	15.1	14.7	15.6	16.4	16.8	16.4	16.5	19.3	19.9	19.6	21.8	19.4
d_L	17.3	19.8	----	18.0	20.0	21.9	19.0	19.5	21.5	19.6	20.3	20.4	20.5	23.5	26.4
$\boldsymbol{d}$	14.0	15.1	----	13.6	14.1	15.1	14.4	14.7	15.6	14.8	16.2	16.4	16.3	18.0	18.7

Table V. **7475 Al Grain Dimensions (μm) from Deformation at 525 $^\circ$C**

(Initial dimensions: d_{ST} = 7.2, d_{LT} = 11.3, and d_L = 13.7 μm, for $\boldsymbol{d}$ = 10.7 μm)

ε	0.05	0.1	0.3	0.6	1.0	1.2
$\dot{\varepsilon}$ (s^{-1})						
10^{-2}						
d_{ST}	----	9.3	9.7	----	10.4	----
d_{LT}	----	17.3	20.7	----	26.1	----
d_L	----	16.4	22.8	----	25.6	----
$\boldsymbol{d}$	----	14.3	17.7	----	20.7	----
5×10^{-3}						
d_{ST}	----	9.1	9.9	10.5	10.5	----
d_{LT}	----	17.8	20.1	24.4	24.8	----
d_L	----	17.7	23.2	25.7	27.3	----
$\boldsymbol{d}$	----	14.9	17.7	20.2	20.9	----
10^{-3}						
d_{ST}	9.2	9.9	10.7	10.2	11.2	14.5
d_{LT}	17.7	18.5	21.5	22.1	23.0	23.3
d_L	16.4	21.3	26.7	29.5	30.7	28.1
$\boldsymbol{d}$	14.4	16.6	19.6	20.6	21.6	22.0
5×10^{-4}						
d_{ST}	9.0	9.5	10.9	11.0	11.6	14.3
d_{LT}	17.7	19.7	21.9	23.8	24.7	25.3
d_L	15.7	23.1	29.6	30.1	32.8	28.8
$\boldsymbol{d}$	14.1	17.4	20.8	21.6	23.0	22.8
10^{-4}						
d_{ST}	8.7	9.5	10.7	12.6	12.1	----
d_{LT}	18.8	22.6	25.4	23.7	25.7	----
d_L	27.9	30.0	36.5	39.8	40.8	----
$\boldsymbol{d}$	18.5	20.7	24.2	25.4	26.2	----

From Table IV: At the three lower deformation temperatures the *level of DEGG*, $\Delta d \equiv d(\varepsilon,\dot{\varepsilon},T) - d_0$, generally increases with: decreasing strain rate for a given temperature and strain, increasing deformation temperature for a given strain and strain rate, and increasing strain at each strain rate; DEGG stands for deformation-enhanced grain growth. At 525 °C the level of DEGG is markedly higher than at 516 °C[72] and there is a much greater effect of strain rate on the grain size. Also at 525 °C, very little additional DEGG occurs for strains greater than $\varepsilon = 0.3$, and similarly at 516 °C for strains greater than $\varepsilon = 0.6$.

Figure 54 shows the grain size as a function of strain for each strain rate at 525 °C, along with curves generated from second-order least-square fits of the data for each strain rate. It appears that at higher strains for the three lower strain rates that limiting grain sizes (d_c) are being approached, and also that d_c increases with decreasing strain rate. Campenni and Cáceres (1988) observed that the grain size of Zn-22% Al-0.5% Cu tended to approach an upper limit during superplastic deformation, and that d_c increased with decreasing strain rate and also with increasing deformation temperature.

Grain growth rates for 7475 Al at 525 °C were determined from Figure 54 by differentiating the curve fits. The resulting grain growth rates are given in Table VI and displayed by Figure 55. The grain growth rates are practically linear in the strain rate (Wilkinson and Cáceres 1984), but only at low strains; **the grain growth rate also decreases with increasing strain for a given strain rate**. Senkov and Myshlyaev (1986)

---

[72]: This is why it was not included in the analyses of grain growth in Section 5 of Chapter Two.

also noted that the grain growth rate for Zn-22% Al decreased with increasing strain; this is attributable to the parabolic grain growth kinetics they used to represent their data. Arieli and Mukherjee (1982) also give grain growth kinetics,[73] $\boldsymbol{d}^2 = cD_B t^N/(1 - \boldsymbol{d}_0/\boldsymbol{d})$, featuring a grain growth rate, $\partial \boldsymbol{d}/\partial t = \mathrm{N} c D_B t^{N-1}/(2\boldsymbol{d} - \boldsymbol{d}_0)$, which decreases with increasing grain size and/or deformation time t; here, c is a constant and N is an exponent, presumably $\mathrm{N} \leq 1$.

Table VI. **7475 Al Grain Growth Rates (μm/s) at 525 °C**

	Strain Rate (s^{-1})				
Strain	10^{-4}	5×10^{-4}	10^{-3}	5×10^{-3}	10^{-2}
0.05	7.20×10^{-3}	4.09×10^{-2}	6.18×10^{-2}	---	---
0.1	3.29×10^{-3}	1.98×10^{-2}	2.95×10^{-2}	1.42×10^{-1}	3.23×10^{-1}
0.3	8.21×10^{-4}	4.45×10^{-3}	7.82×10^{-3}	4.54×10^{-2}	9.68×10^{-1}
0.6	2.79×10^{-4}	1.18×10^{-3}	2.84×10^{-3}	2.20×10^{-2}	---
1	1.03×10^{-4}	2.23×10^{-3}	1.21×10^{-3}	1.19×10^{-2}	1.99×10^{-2}

Grain growth rates for 7475 Al are of the order 10^{-4} μm/s during the onset of annealing and decrease with increasing grain size thereafter. Superplastic deformation therefore increases the rate of grain growth by over an order of magnitude, depending on the strain, strain rate, and deformation temperature.

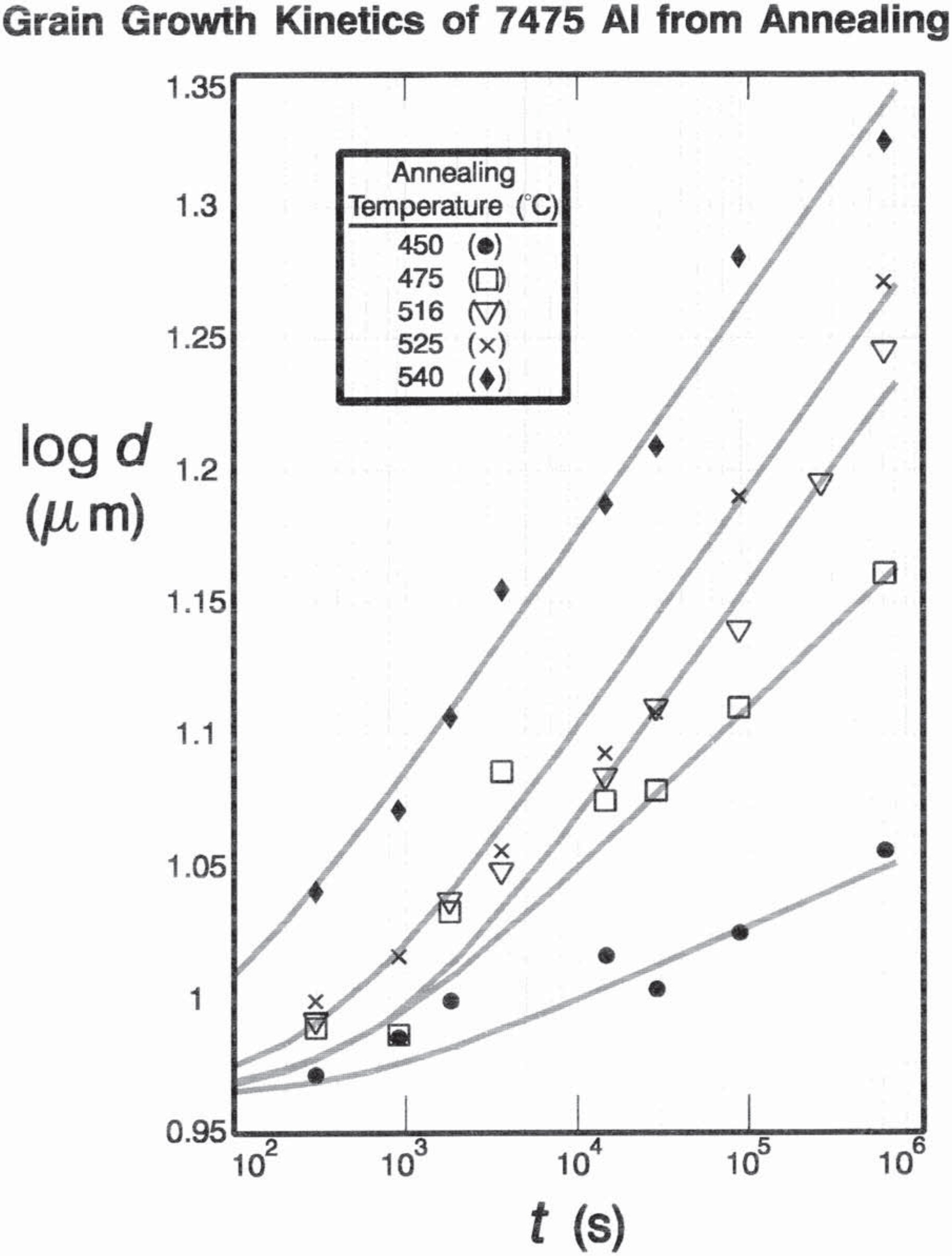
---

[73]: They do not, however, attribute these grain growth kinetics to a particular mechanism for deformation-enhanced grain growth.

FIGURES 53-55

Figure 53. Using the parameters *K* and n from Table III, equation (1) is shown with the 7475 Al data from Table II. The curves shown are an empirical representation of the grain growth kinetics (***d*** as a function of *t* and *T*) of 7475 Al during annealing. The grain growth exponent n is always much less than 1/2, and n decreases with decreasing temperature. The 7475 Al alloy therefore exhibits "non-ideal" grain growth during annealing. See Sherwood and Hamilton (1993) for further discussion.

Figure 53 (Continued).



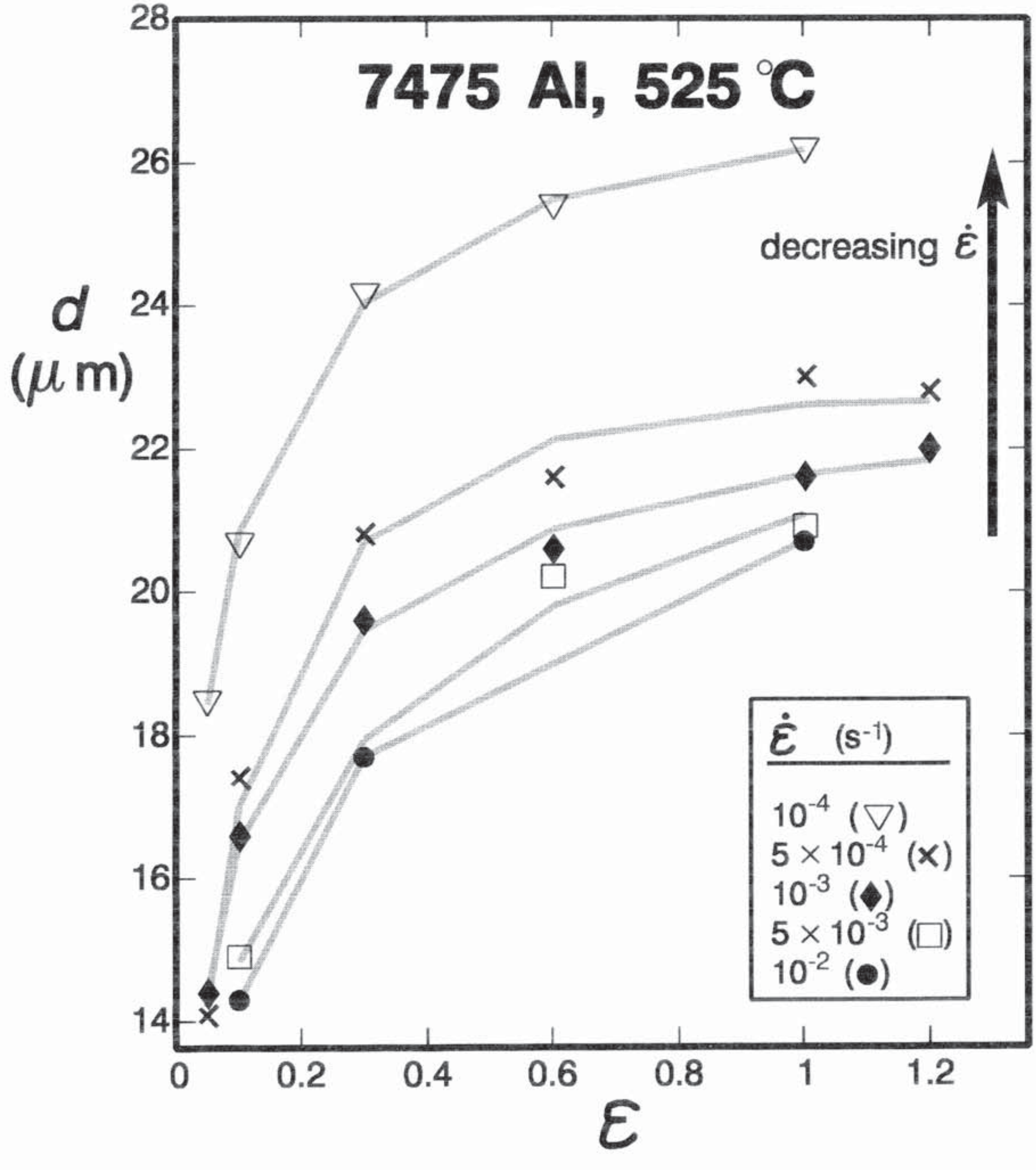


Figure 54. Deformation-enhanced grain growth of 7475 Al at 525 °C. Average grain sizes, $\boldsymbol{d} = \boldsymbol{d}(\varepsilon, \dot{\varepsilon} = const.)$, are shown as a function of strain ε for each strain rate $\dot{\varepsilon}$, against curves generated from second-order least-squares fit polynomials of $\boldsymbol{d}(\varepsilon, \dot{\varepsilon} = const.)$.

Figure 55. Grain growth rates of 7475 Al for superplastic deformation at 525 °C. Grain growth rates were obtained by differentiating the least squares fit polynomials displayed by Figure 54 with respect to strain: $[\partial \boldsymbol{d}(\varepsilon, \dot{\varepsilon} = const.)/\partial\varepsilon]\dot{\varepsilon} = \dot{\boldsymbol{d}}(\varepsilon, \dot{\varepsilon} = const.)$. This relationship is then used to obtain values for $\dot{\boldsymbol{d}}(\varepsilon = const., \dot{\varepsilon})$ for $\varepsilon = 0.1, 0.3, 1.0$, which is the function displayed here. Data resulting from this analysis are recorded in Table VI.

The grain growth rate decreases with increasing strain for a given strain rate. For the lower strains the grain growth rate is approximately proportional to the strain rate, $\dot{\boldsymbol{d}} \propto \dot{\varepsilon}$; at $\varepsilon = 1$, $\dot{\boldsymbol{d}} \propto \dot{\varepsilon}^{1.2}$ because the grain growth rate is diminished at low strain rates.

Figure 55 (Continued).